Spatiotemporal dynamics of a shallow fluidized bed

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ABSTRACT: An experimental and theoretical study of the dynamics of an air-fluidized thin granular layer is presented. Near the threshold of instability, the system exhibits critical behavior with remarkably long transient dynamics. Above the threshold of fluidization the system undergoes a Hopf bifurcation as the layer starts to oscillate at a certain frequency due to a feedback between the layer dilation and the airflow rate. Based on our experimental data, we formulate a simple dynamical model which describes the transition in a shallow fluidized bed.

1 INTRODUCTION

Fluidized beds are widely used in industry for mixing solid particles with gases or liquids (Howard 1989). A uniform fluidization which is the most desirable regime of operation of industrial fluidized beds, is prone to instabilities. As the fluid flow increases, bubbles of clear fluid are formed at the bottom of the bed and these bubbles travel to the surface. The study of mechanisms of fluid bed instabilities and the classification of ensuing regimes (slugging, bubbling, etc) has been an active area of research among engineers and physicists. The research has been mainly focused on deep fluidized beds whose vertical dimension is larger than the characteristic size of the bubbles and (typically) the horizontal dimensions of the chamber.

Much less attention has been devoted to the study of shallow fluidized beds (Schafinger et al. 1997). When the height of the bed is much smaller than its horizontal size and characteristic bubble size for an equivalent deep bed, no bubble formation can be expected. A natural question arises on what sequence of regimes leads to a developed turbulent fluidized state in that system. Because of the large aspect ratio, the dynamics is effectively two-dimensional, which allows one to gain much information by imaging the bed from above. In (Tsimring et al. 1999), we studied the onset of fluidization and found that it has the features of a phase transition, with very long transient fluctuations just below the fluidization threshold.

Here we report the results of the experimental study of the thin granular layer dynamics at high airflow rates, when all layer becomes fluidized. Above this

threshold the layer begins to oscillate at a certain frequency which depends on the layer thickness and the airflow rate. Processing of surface images revealed the occurrence of propagating waves which form small disordered short-lived spirals. At larger airflow rate, irregular small-scale oscillating cellular pattern appears on the surface of the bed. The frequency of these oscillating bubbles is significantly less than that of large-scale waves. The mechanism of layer oscillations is related to the dependence of the drag force from the air flow acting on the granular layer, on the volume fraction of particles in the layer. When the layer is dilated, the drag force diminishes, and the layer falls back due to gravity. This picture leads us to the formulation of the simple dynamical model which qualitatively agrees with our experimental results.

2 EXPERIMENT

The experiments were performed in an open cylindrical Plexiglas cell. The bottom plate was made of a sintered bronze with an average pore size $6\text{ }\mu\text{m}$, thickness 0.5cm , and diameter 15cm . Dry air was pumped through the layer of monodisperse spherical bronze particles of size 0.15 mm , and the bed depth was varied from 3 to 7 particles deep. The patterns on the surface of the granular layer were illuminated using low-angle light from a circular fluorescent light around the bed, and recorded by high-speed Kodak SR-C digital CCD camera. We also used a pressure transducer Sensym SX01DP1 to record the airflow fluctuations near the free surface of the granular layer.

When the flow rate is below certain threshold value,

Figure 1: Power spectrum of the pressure fluctuations near the layer at the airflow rate 15.8 cm/sec. The arrow indicates the peak corresponding to the large-scale layer oscillations.

the layer remains completely static. The value of this critical airflow depends sensitively on the grain parameters (size, shape, density) as well as on the thickness of the layer. Unless explicitly noted otherwise, we will be referring to the bed thickness 0.65 mm. For that thickness, the critical airflow speed was 12.1 cm/sec. Slightly below the threshold, the system exhibits very long transient behavior: after a tap on the side wall, the localized regions of fluidized particles remain active for a long time before the activity ceases, and the bed returns to a completely static regime. In (Tsimring et al. 1999), we studied this transition, and proposed a simple cellular automata model which explained the main features of this transition. Slightly above the threshold, the fluidization of the layer is persistent, but remains highly non-uniform in space.

At a higher flow rate, the whole layer becomes fluidized and exhibits noticeable vertical oscillations. The power spectrum of the pressure fluctuations near the free surface of the layer is shown in Figure 1. We measured the peak frequency and the magnitude as a function of the airflow velocity. The amplitude of the oscillations increases linearly and the frequency f slightly decreases as the airflow speed increases. Figure 2a shows dependence of the peak frequency on the airflow speed for different values of layer thickness. A naive scaling of variables by the gravity g and the thickness of the layer h_0 ($f(h_0/g)^{1/2}$, $V(gh_0)^{-1/2}$) does not converge these data to a single curve. It indicates that additional non-dimensional parameters involving the particle size d and the air viscosity ν play an important role in the mechanism of these oscillations. For example, if one chooses scaling $Vd/(h_0^3g)^{1/2}$ for the airflow, then the data lie rather close to a single curve (see Fig.2b).

High-speed imaging of the surface at 500 fps also confirms the occurrence of the layer oscillations. In order to determine the spatial structure of these oscillations, we performed temporal filtering of the recorded image sequences. We used a band-pass filter to extract oscillations at the peak frequency f for each pixel, and then combined these filtered signals

Figure 2: a - frequency f of the spectral peak in the power spectrum of layer oscillations as a function of the airflow rate V ; b - rescaled frequency $f(h/g)^{1/2}$ as a function of $Vd/(gh_0^3)^{1/2}$

Figure 3: Spatial structure of the 0.65 mm layer oscillations: a - snapshot of the granular layer surface for $V = 15.8$ cm/sec; b - corresponding snapshot from the temporal sequence filtered by the narrow-band filter with central frequency $f = 35$ Hz; c - spatial distribution of the phase of 35 Hz oscillations; d - snapshot from the temporal sequence for $V = 42.2$ cm/sec filtered by a low-pass filter with the cutoff frequency 25 Hz.

Figure 4: Azimuthally-averaged spatial power spectrum of oscillations at the dominant frequency 31.2 Hz (dashed line) and low-frequency oscillations $f < 25$ Hz (solid line) for the airflow speed 42.2 cm/sec

back to create the sequence of filtered images (cf. (La Porta and Surko 1998; Lin 2000)).

A raw snapshot from the video sequence taken at the airflow speed 15.8 cm/sec, and the corresponding filtered snapshot are shown in Figure 3a,b. A movie formed out of the filtered images (see <http://inls.ucsd.edu/grain/fluidbed>) revealed that the oscillations form propagating waves, moreover, these waves are organized in small irregular spirals. The sense of direction of the wave propagation can be seen from the spatial distribution of the phase of oscillations at the filtered frequency f (Figure 3c). Singularities of the phase correspond to the cores of the spirals, or topological defects. The phase distribution changes over time, as the defects move, annihilate, and new defects are born. Such “defect turbulence” is to be expected near the onset of the Hopf bifurcation in spatially extended systems. It is generically described by the Ginzburg-Landau equation for the complex amplitude of the oscillation (Chate and Manneville 1996). Similar defect turbulence has been observed in spatially-extended Belousov-Zhabotinsky reaction by Ouyang and Flesselles (1996).

At higher air flow, in addition to large-scale layer oscillations, irregular small-scale perturbations of the layer appear. These perturbations correspond to the low-frequency part of the layer oscillations spectrum. Figure 3d shows the snapshot of the surface image at the airflow 42.2 cm/sec obtained by low-pass filtering of the image sequence with the cut-off frequency 25 Hz. The spatial power spectrum of these perturbations averaged over angle is shown in Figure 4 together with the corresponding spectrum for the peak frequency 31 Hz. As one can see, spatial spectrum of low-frequency oscillations exhibit a broad peak at wavenumber $k \approx 1.6 \text{ cm}^{-1}$, whereas the spectrum of 31 Hz oscillations decays with the wavenumber.

3 MODEL

The mechanism of the shallow fluidized bed oscillations can be described as follows. The layer dynamics are determined by the interplay of two forces: gravity and the drag force from the gas flow. While gravity g remains constant, the drag force varies depending on the volume fraction of particles in the layer. When the layer lies on the surface and is densely packed, the drag force is maximal. On the other hand, when the layer is lifted in the air and diluted, it becomes more “transparent” for the airflow, and the drag force decreases. This effect is known for deep fluidized beds (Batchelor 1999). In the simplest form, we could assume that the drag force Γ is inversely proportional to the height of the layer h , $\Gamma = \gamma/h$, where constant γ depends on the nominal flow speed V , close-packed thickness of the layer h_0 , gas viscosity, and the properties of the individual particles (size, shape). Assuming that the bottom of the layer does not leave the floor of the bed, and the layer is uniformly diluted, the average vertical acceleration of the layer is $h_{tt}/2$. Then the second Newton’s law yields

$$h_{tt} = \frac{2\gamma}{\rho h} - 2g, \quad (1)$$

where subscript t denotes time derivative, and ρ is the total mass of grains per unit area. In non-dimensional variables $H = h/h_0$ and $T = (2g/h_0)^{1/2}t$, this equation reads

$$H_{TT} = \frac{P}{H} - 1, \quad (2)$$

where $P = \gamma/\rho gh_0$. The amplitude A and frequency of periodic oscillations Ω for this nonlinear oscillator equation depend on the initial conditions. Assuming that the layer always comes down to the surface where it has a minimal thickness h_0 , we impose initial conditions $H(0) = 1$ and $H_T(0) = 0$. With these initial conditions, the amplitude and frequency of oscillations are uniquely determined by the parameter P . For P slightly above 1, the amplitude of oscillations $A \approx P - 1$ and the frequency is $\Omega \approx P^{-1/2}$. So, in qualitative agreement with the experiment, near the threshold the amplitude increases approximately linearly with P , and the frequency slowly decreases with P .

While the model Eq.(1) explains the nature of the layer oscillations, it does not address the mechanism of the instability which leads to the oscillations. Indeed, since there is always some dissipation due to friction and inelastic particle collisions, the oscillations would decay, and the stable equilibrium bed thickness at which the drag force balances gravity, would be reached. To overcome dissipation, an additional instability mechanism is needed to excite the layer oscillations. The mechanism of this instability is related to the known mechanism of instability for

deep fluidized beds (Batchelor 1999), in which it is caused by the inertia of particles in the gas flow and leads to the time delay between the volume fraction variations and the drag force changes. Similarly, we can assume that the drag force Γ is not enslaved to the thickness the layer h , but approaches γ/h asymptotically. This additional degree of freedom can be described by the equation $\alpha\Gamma_t = \gamma h^{-1} - \Gamma$, where parameter α controls the rate of inertia in the dependence between Γ and h . We shall also modify the equation for the layer thickness dynamics (1) to include a thickness-dependent dissipation. Indeed, the amount of dissipation varies strongly as a function of the layer thickness, as it affects the frequency of inelastic collision among grains. As the thickness approaches the close-packed limit, the number of collisions, and the dissipation rate, diverge. We assume that this effect is captured by an additional dissipative term $-\sigma h_t/(h - h_0)^2$ (the actual power of singularity at $h = h_0$ is not important here). Now, the extended model in non-dimensional form reads

$$H_{TT} = F - 1 - \frac{\sigma' H_T}{(H - 1)^2}, \quad (3)$$

$$\alpha' F_T = \frac{P}{H} - F, \quad (4)$$

where $F = \Gamma/g\rho$, $\alpha' = \alpha(g/h_0)^{1/2}$, $\sigma' = \sigma(gh_0^3)^{-1/2}$. Additional relaxation dynamics described by Eq.(4) directly leads to an instability of the thin fluidized layer. Linearizing Eqs.(3),(4) near the fixed point $F = 1$, $H = P$ we obtain the dispersion equation for perturbations $\propto \exp(-i\Omega T)$,

$$(1 - i\alpha\Omega) \left[\Omega^2 + \frac{i\sigma\Omega}{(P - 1)^2} \right] = \frac{1}{P}, \quad (5)$$

where we dropped primes at the non-dimensional parameters α and σ . At small α and σ , the complex frequency of layer oscillations is given by

$$\Omega \approx P^{-1/2} + \frac{i}{2} \left[\frac{\alpha}{P} - \frac{\sigma}{(P - 1)^2} \right]. \quad (6)$$

As one can see from this formula, the instability always occurs at large enough P . Notice that for small α and σ , the solution of Eqs.(3),(4) at large T approaches that of Eq.(2) with initial conditions $H(0) = 1$; $H_T(0) = 0$. This is not surprising, since these conditions are enforced by diverging dissipation rate at $H = 1$, and during the rest of the oscillation cycle, non-conservative corrections are negligibly small.

4 CONCLUSIONS

To conclude, in this paper we described the transition to a fluidized state in a shallow granular layer.

Experiments with air-driven shallow fluidized beds showed that above the threshold of fluidization the system exhibits a Hopf bifurcation as the layer starts to oscillate due to the feedback between the layer dilation and the airflow drag force. Temporal band-pass filtering of the spatiotemporal data revealed long propagating waves forming defect turbulence. At high flow rates, low-frequency short-wavelength structures ("bubbles") appear in addition to the long-wavelength excitations.

We proposed a simple dynamical model describing high-frequency oscillations, in which the layer is driven by the airflow drag force and gravity. The drag force depends on the volume fraction of particles in the layer, and therefore on the height of the layer surface. This feedback leads to an oscillatory instability. The model predictions agree on a qualitative level with the observed dependence of the oscillation magnitude and frequency on the airflow rate.

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REFERENCES

- Batchelor, G. K. (1999). A new theory of the instability of a uniform fluidized bed. *J.Fluid Mech.* 193: 75–110.
- Chate, H. and P. Manneville (1996). Phase diagram of the two-dimensional complex ginzburg-landau equation. *Physica A* 224: 348–368.
- Howard, J. R. (1989). *Fluidized bed technology: principles and applications*. Bristol; New York: A.Hilger.
- La Porta, A. and C. M. Surko (1998). Quantitative characterization of 2d traveling-wave patterns. *Physica D* 123(1-4): 21–35.
- Lin, A. L. (2000). Resonant phase patterns in a reaction-diffusion system. *Phys. Rev. Lett.* 84(18): 4240–4243.
- Ouyang, Q. and J.-M. Flesselles (1996). Transition from spirals to defect turbulence driven by a convective instability. *Nature* 379: 143–146.
- Schaffinger, U., T. Aihara, T. Gruber, U. Weingerl, et al. (1997). Analysis of particle motion in a very shallow fluidized bed. *Int.J.Multiphase Flow* 23(3): 455–471.
- Tsimring, L. S., R. Ramaswamy, and P. Sherman (1999). Dynamics of a shallow fluidized bed. *Phys. Rev. E* 60(6): 7126–7129.